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Coastal Studies Institute
Center for Wetland Resources
Louisiana State University
Baton Rouge, Louisiana 70803

Technical Report No. 230

DEVELOPMENT OF THE ACTIVE LAYER, PINGOK ISLAND, ALASKA

By Douglas M. Fisher

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ABSTRACT

Depth-of-thaw measurements were made on Pingok Island, Alaska, throughout the 1972 thaw season. The research revealed that initial thaw is rapid and the rate decreases exponentially until a maximum depth is reached. Generally, the base of the active layer conforms to the surface configuration; however, local variations in the rate of thaw affect the shape and thickness of the active layer. An inversion of the surface topography often develops beneath hummocks that have a low vegetation cover and over ice wedges that are close to the surface. Slope exposure was found to be significant in affecting the thickness of the active layer, whereas moisture content and sediment size of the range discovered on Pingok Island have only minor effects on the depth of thaw. Thaw depths beneath a shallow pond were found to be greater than on the surrounding tundra. The dominant factor in influencing the thickness of the active layer in the study area is considered to be the presence of a vegetation cover.

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INTRODUCTION

Within the past decade, discoveries of oil and gas in northern Alaska and arctic Canada have resulted in a sharp increase in the level of economic activity in these areas. Without adequate precautions, major construction projects planned for the region could cause irreparable environmental damage. Of particular concern is damage to the active layer and resulting degradation of the permafrost.

The active layer is a surficial layer above the permafrost that annually thaws and freezes. Permafrost, usually defined on the basis of temperature, is soil or rock that has remained below 0°C continuously for more than 1 year. Permafrost underlies about 20 percent of the world's land area, including approximately 50 percent of Canada and 85 percent of Alaska (Ferrians and Hobson, 1973).

Although an understanding of the active layer is critically important to an understanding of geomorphic processes operating in the Arctic, very few detailed studies on the active layer are available. The purpose of this report is to present an analysis of the factors that are responsible for variations in the shape and thickness of the active layer under natural conditions.

Field work for this project was carried out on Pingok Island, located off the coast of northern Alaska (Fig. 1). The depth of thaw on Pingok was monitored by probe measurements over a thaw season, from June 4 to September 12, 1972.

The data were collected along transects established in environments which varied from dry, sandy, unvegetated sites to saturated, highly vegetated soils. The data were analyzed in graphical form and supported by statistical interpretation. The relationship between the shape and thickness of the active layer and various environmental factors, including topograpny, exposure, vegetation, sediment size, and moisture content, is discussed.

Previous Studies

Although numerous authors have recorded depth-of-thaw data, detailed studies on the development of the active layer are still scarce. Bliss and Wein (1971) and Brown and Péwé (1973) have shown the need for additional studies related to collection and analysis of depth-of-thaw data. Although depth-of-thaw observations are frequently presented in the literature, there is generally little discussion or analysis of the measurements. In addition, many published measurements do not represent the maximum thickness of the active layer because measurements were terminated before the end of the thaw season (Brown, 1971).

Cook (1955), one of the earliest to undertake a detailed study of the active layer, concentrated on the amplitudes and time lags of daily and monthly soil temperatures. Studies by Drew et al. (1958) concluded that depth of thaw is related to soil type. Annersten (1966) recorded insignificant temperature variations in the active layer among most types of vegetation. This finding concurs with that of

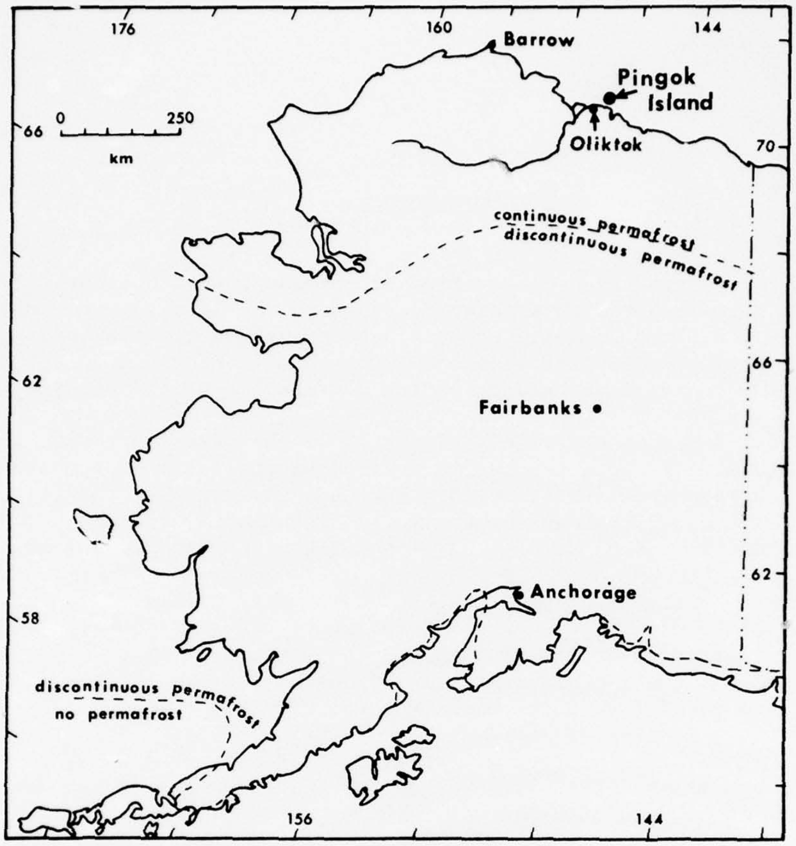


Figure 1. Location map and permafrost zones in Alaska (after Brown and Péwé, 1973).

Bliss and Wein (1971), who found that the depth of thaw is influenced more by soil texture and internal drainage than by vegetation. However, others have concluded that vegetation differences are important and significantly affect the depth of thaw (Brown, 1966; Price, 1971; Zoltai and Tarnocai, 1971). Additional conflicting conclusions appear in the literature. For example, Price (1971) found a thicker active layer on the southwest slope than on the southeast slope, but French (1970) indicates that the reverse situation prevails at his study location.

Two contrasting concepts exist concerning the shape of the active layer. One, advanced by Mackay (1958), contends that the base of the active layer, which is also the top of the permafrost surface, does not follow the contour of the ground but is an inversion of the surface profile. According to this concept, the active layer is generally at a higher elevation beneath surficial depressions than it is beneath hummocks (Fig. 2A). Brown and Johnson (1965) have advanced the second and more widely accepted view, that the base of the active layer is nearly a replica of the surface configuration (Fig. 2B).

Other research on the active layer has been conducted by those interested in disturbance studies. Mackay (1970), for example, relates thermokarst subsidence

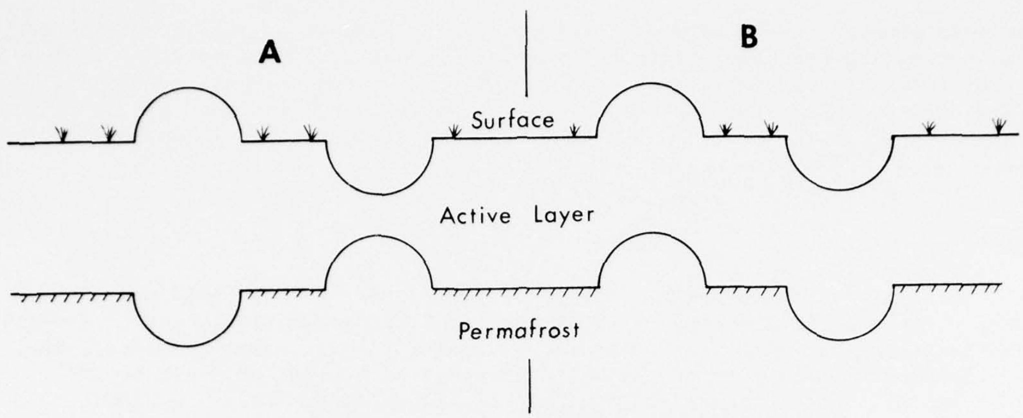


Figure 2. Idealized shapes of the active layer (A after Mackay, 1958, B after Brown and Johnson, 1965).

and deepening of the active layer to disturbances of the tundra surface. A number of recent studies (Kerfoot, 1972; Hernandez, 1972) have dealt with the detrimental effects of vehicle tracks on the tundra. Natural disturbances such as forest fires have also been shown to be responsible for increases in the depth of the active layer (Heginbottom, 1971).

Reports on arctic geomorphology often contain active layer measurements. For example, McDonald and Lewis (1973) have recorded the position of the frost table in deltas and river channels. Others, concerned with coastal geomorphology, have determined thaw depths on arctic beaches (McCann and Hannell, 1971; Taylor, 1973).

Physical Setting

Physiography

Pingok Island, located in the Arctic Coastal Plain, the northernmost of the Alaskan physiographic provinces, is underlain by Cretaceous bedrock. The overlying unconsolidated marine sediments are known as the Gubik Formation. These are recently emerged gravels, sands, silts, and clays of Pleistocene and Recent age. Large amounts of peat and ice are also included in the formation (O'Sullivan, 1961; Black, 1964).

The Arctic Coastal Plain is characterized by low relief, numerous shallow oriented lakes, and meandering rivers. Deltaic, fluvial, lacustrine, and eolian processes have modified many of the original environments. Permafrost-associated features such as thaw lakes, beaded streams, ice wedges, and polygons are prevalent throughout the region, and most are represented on Pingok. Along the coast and river banks, waves and thermal erosion have resulted in slumping and shoreline retreat.

Pingok Island is 6.5 km long and varies in width from 250 metres to 800 metres. Elevations on the island are generally 2.5 metres to 3.5 metres, and maximum elevation is 5 metres. At one time Pingok Island was likely part of the

mainland; however, thermokarst subsidence created Simpson Lagoon, a shallow body of water separating the island from the mainland. Because Pingok is now a tundra remnant forming a barrier island, common tundra features such as thaw lakes, ice wedges, and polygons occur on the island. Changes in the shape of Pingok Island as a result of thermal erosion and wave activity are described in Short (1973) and Wiseman et al. (1973).

Climate

The climate of the North Slope is characterized by long, cold winters and short, relatively cold summers. Along the coast the marine influence of the Arctic Ocean is strong in summer, as evidenced by frequent fogs. Even in winter, when the ocean is frozen, temperatures are slightly modified because of maritime influence. Strong and persistent winter winds along the arctic coast result in blowing and drifting of snow and low sensible temperatures.

Daily maximum air temperatures, as recorded at Barrow, rise above freezing during the first week of June and remain above freezing until mid-September. In coastal areas, snow begins to melt in May, and by the second week of June the tundra is usually snow free. By the last week of September small ponds and lakes usually begin to freeze and the snow cover returns. During the 8 to 9 months of winter, the Arctic Slope is covered by a thin, almost continuous veneer of dry, wind-packed snow (Benson, 1969; Lewellen, 1972).

Precipitation is highly variable both temporally and spatially. Approximately half the total mean annual precipitation falls during the thaw season. However, during August, the month of maximum precipitation, amounts ranging from a trace to 71 mm have been recorded at Barrow (Lewellen, 1972). The inherent inaccuracy of snow gages and indirect evidence suggest that the actual precipitation at Barrow may be more than four times the mean of 109 mm (Black, 1954).

Because few climatic records are available for the North Slope, the data recorded at Barrow and Barter Island have often been used as typical of the arctic coast. However, published records were obtained for Oliktok, a Distant Early Warning (DEW) station located on the mainland less than 15 km southwest of Pingok Island (Fig. 1). Records for Barrow and Oliktok show that during late spring temperatures are similar, whereas during July and August Oliktok, on the average, is slightly warmer than Barrow (Fig. 3). The temperature regimen for May and June 1972 followed the normal pattern; however, for the remainder of the season Barrow was warmer than Oliktok. The temperature for the 1972 summer at Barrow, as indicated by the degree day curve, lies close to the 30-year mean; however, at Oliktok the summer was cooler than average (Fig. 3).

Vegetation

The Coastal Plain, apart from small areas of erosion or recent sedimentation, is covered by a continuous mat of tundra vegetation. Grasses and sedges, generally less than 10 cm high, as well as prostrate willows and occasional flowering herbs, typify the coastal vegetation. Perennial rhizomatous grasses having shallow roots survive well, as do plants that are adaptive to the general wetness of the Coastal Plain (Britton, 1957; Spetzman, 1959).

The composition of the plant communities on Pingok Island is similar to that described in the literature for the Barrow area. A minimum of 28 species from 19

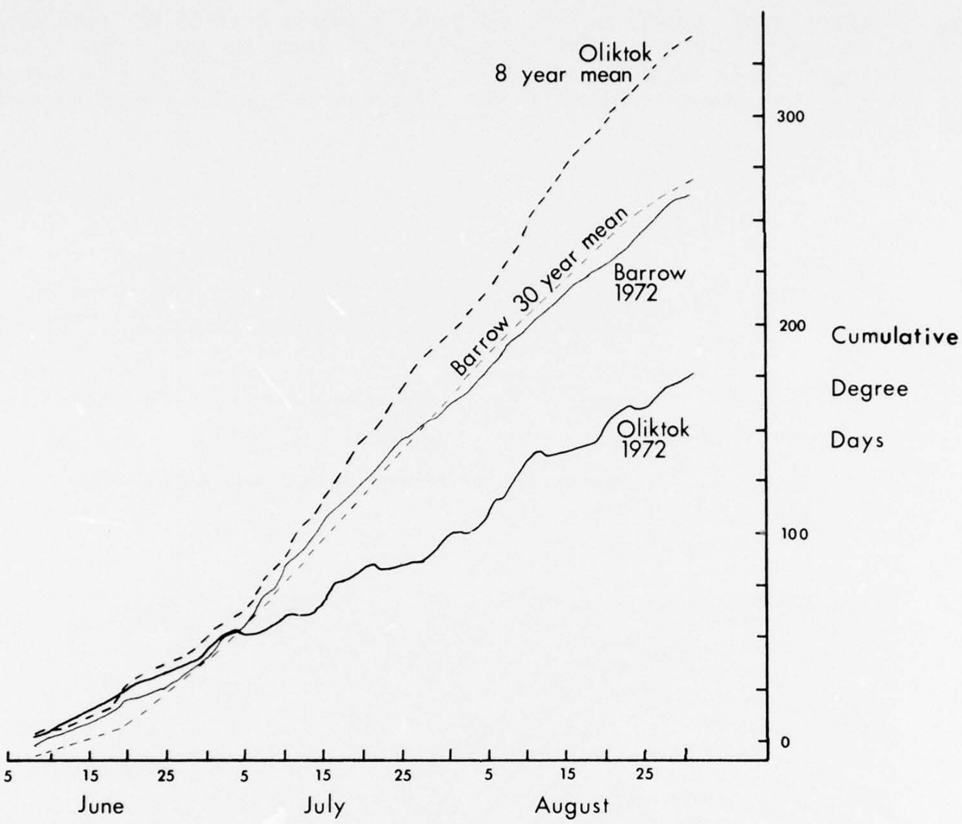


Figure 3. Cumulative degree days computed from air temperatures recorded at Barrow and Oliktok (adapted from Lewellen, 1972).

orders occurs on Pingok (Appendix A). Three distinct vegetative zones occur on the island: dunal, flotsam, and wet sedge communities (Figs. 4 and 5). A sand dune complex occurs sporadically along the northern shore of the island. Elymus arenarius ssp. mollis was the only species identified within the dunal complex. The flotsam community, a sparsely vegetated band, occurs intermittently along the northern shore and inland of the dunal community. Alopecurus alpinus, Petasites frigidus, Stellaria longipes, and Cochearia officinalis are the principal members. The flotsam community was formerly well vegetated, but a severe storm in 1970 destroyed the vegetation and deposited a thin veneer of sand on top of the peat and organic mat. The width of this zone ranges from 0 to 45 meters. At various sites within the flotsam community, the percentage of leaf cover in a 0.5-metre-square grid ranges from 0 to an estimated 30 percent. The 1970 storm also caused the removal of vegetation from a zone less than 10 metres wide along the southern shore of the island.

Sparseness of the flotsam community contrasts sharply with the wet sedge community, where the percentage of leaf cover in a 0.5-metre grid is generally 80 percent to 95 percent. Lichen, moss, or bar soil accounts for the remaining percentage.

Carex aquatilis, the dominant species, occurs in poorly drained habitats such as the center of polygons. Where the drainage is better, as on the small ridges surrounding the polygon, or on hummocks, the percentage of other species, particularly Salix and Poa, increases. Lichens and mosses are also prevalent throughout the community.

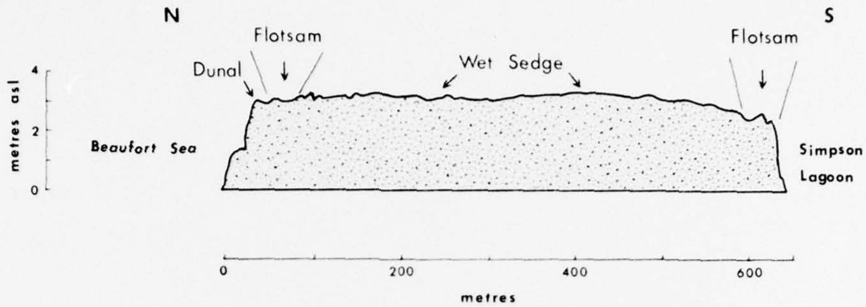


Figure 4. Cross section of Pingok Island and major vegetation communities.

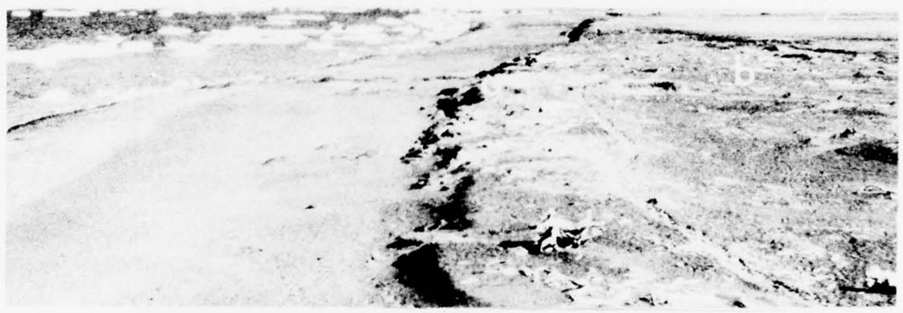


Figure 5. Northern shore of Pingok Island (view to the east). Note the dunal (a), flotsam (b), and wet sedge (c) communities.

Soils

Soil-forming processes in arctic regions are strongly influenced by permafrost. Low soil temperatures and a short growing season result in a very slow rate of organic synthesis and decomposition. Many patterned ground features such as frost boils are the result of particle sorting by cryoturbation. Under these conditions, the acquired soil morphology is disrupted, precluding the use of conventional soil horizon nomenclature (Tedrow et al., 1958; Tedrow, 1973).

In summer, as the ground thaws, considerable quantities of water become available, and, as the underlying permafrost is impervious, drainage must be lateral. As a result, most soils are poorly drained. Under these conditions, gleization accounts for the primary soil-forming process. Drainage is further affected by permafrost-associated features such as polygons. The ridges surrounding polygons are better drained than the troughs or flat areas. In such areas of little or no runoff, organic matter tends to accumulate and soils high in organic content

develop (Tedrow et al., 1958).

The soils of Pingok Island belong to the silty and generally acidic Tundra soil group, the most common type on the Coastal Plain (Fig. 6). Drainage irregularities, changes in the amount of organic matter, and the complex pattern of ice

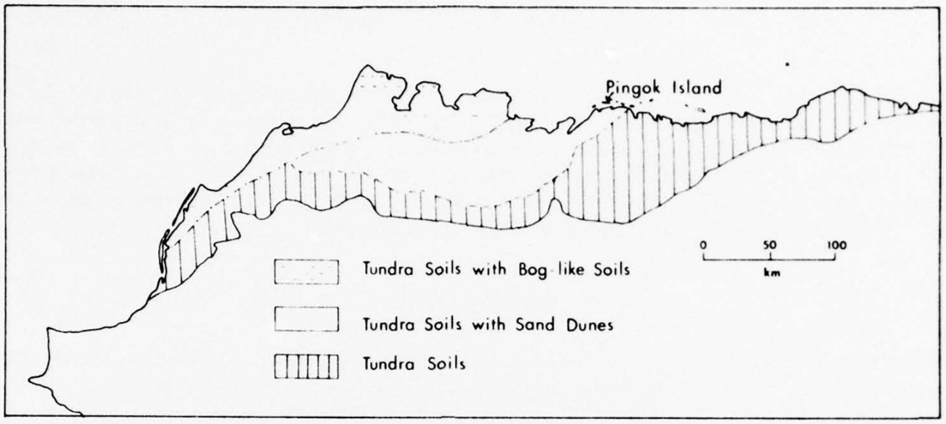


Figure 6. Soil distribution on the Arctic Coastal Plain (after Tedrow and Brown, 1962).

in the form of lenses, wedges, and veins result in considerable variation among profiles. Although complete soil profiles were not examined on Pingok Island, four major horizons are normally recognized in Tundra soils: surface organic, upper mineral, buried organic, and frozen substrate (Tedrow et al., 1958; Fig. 7).

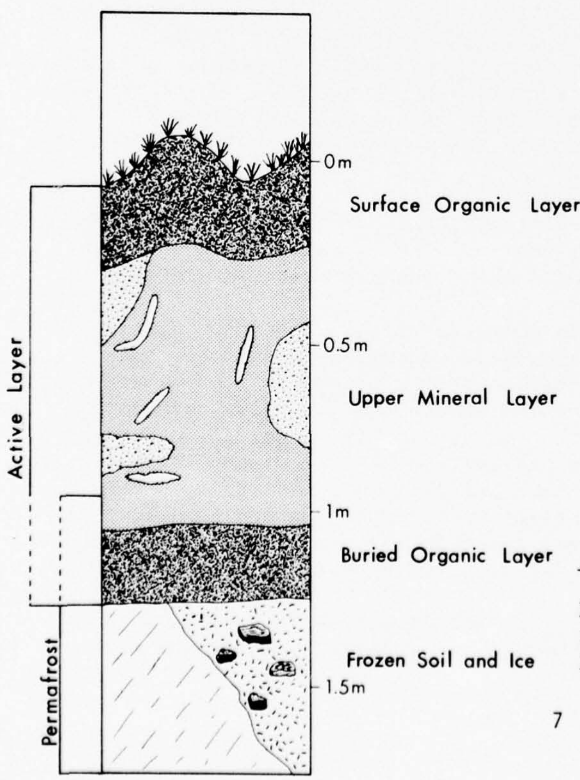


Figure 7. Idealized Tundra soil profile (after Tedrow et al., 1958; Tedrow, 1973).

INVESTIGATIONS AND PROCEDURES

The field station of the Naval Arctic Research Laboratory on Pingok Island was used from June 4 to September 12, 1972, to make observations and probe measurements of the active layer. In early June, snow accumulations on Pingok varied from scattered patches on the wind-swept northern side of the island to a mean depth of approximately 30 cm on the southern portion. Large snow drifts were present on the beach and bluff along the northern and southern shores.

Field Methods

The depth of thaw was measured by inserting a pointed steel rod into the soil to the point of refusal. The rod, about 1 cm in diameter, was graduated in 1 cm intervals. Measurements by other investigators (Brown and Johnson, 1965; Brown et al., 1970) using this technique have been found accurate to within 1 cm. Test pits dug on the tundra in mid-June indicated that similar accuracies could be expected. However, in sands and gravels the depth of thaw was difficult to determine, and inaccuracies of several centimetres could have occurred. As the active layer thickened, the discrepancy between the recorded and actual thickness of the active layer increased. Near the time of maximum thaw, when the active layer was more than 100 cm thick, variations of up to 12 cm occurred in the depth-of-thaw measurements.

Four sites (stations 2N, 17N, 22N, and 24S) were selected along section A of a transect across the island where depth-of-thaw and soil temperatures were recorded, generally on a daily basis, throughout the summer. Commercial soil thermometers were used to determine temperatures at depths of up to 40 cm. Three of the sites (stations 2N, 17N, and 22N) were located within the sparsely vegetated flotsam community, and the fourth (station 24S) was located on a polygon ridge within the wet sedge community (Fig. 8).

The development of the active layer was monitored throughout the thaw season along transects established within several environments. Transects were established across the island, a polygon, a pond, and on several oriented slopes.

The transect across Pingok Island was composed of two sections. Section A was 58 metres long and oriented at right angles to the northern shore of the island (Fig. 8). The first 10 metres of the transect crossed the flotsam community; however, by the 20-metre mark, the transect was within the wet sedge community (Fig. 9). Readings were taken along the transect at 1-metre intervals. Section B was 480 metres long and crossed vegetation and terrain typical of the island (Figs. 8 and 10). Along this portion of the transect readings were made every 5 metres. Thaw depths along both sections of the transect were recorded approximately every 7 days at the beginning of the thaw season. Later in the summer, when the rate of thaw decreased, the frequency of readings was reduced to every 10 to 14 days.

Four transects, ranging between 16 metres and 28 metres in length, were established across a polygon typical of those on the island. Thaw depths were

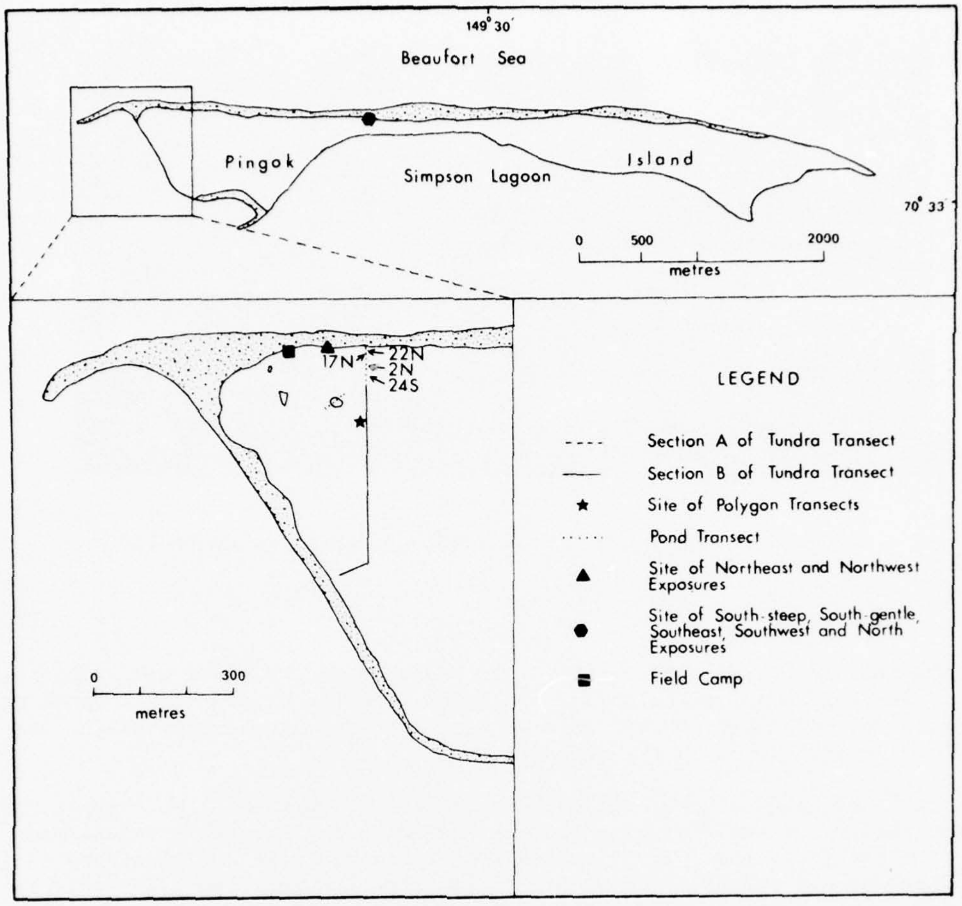


Figure 8. Map of Pingok Island showing transect locations.

Figure 9. Section A of the tundra transect (view to the north).

Figure 10. Section B of the tundra transect (view to the north).

at 1-metre intervals along the transects in order to record minor variations in the depth of thaw that might occur across a polygon. Depth-of-thaw measurements across the polygon were recorded every 7 days at the beginning of the thaw season and every 10 to 14 days later in the summer.

A total of seven slopes, one each facing north, northeast, northwest, southeast, southwest, and two facing south, were selected and transects established to monitor the depth of thaw (Fig. 8). Suitable east- and west-facing slopes could not be found on the island. The slopes ranged from 0.8 metre to 1.2 metres in height and from 2.5 metres to 5.5 metres in horizontal length, and resulting angles were between 10° and 22°; these were among the steepest undisturbed slopes on the island. Depth-of-thaw measurements were taken three times during the season at 0.5-metre intervals along the transects.

Because large amounts of heat can be stored in water, the thermal regime and hence the depth of thaw beneath ponds may differ from those of the surrounding tundra. Accordingly, a transect with readings at 1-metre intervals was placed across a small pond on the island (Fig. 8). The pond was circular and had a diameter of approximately 20 metres; because it was only 7 cm deep, the pond froze to the bottom in winter. A thick, silty, organic ooze covered the bottom of the pond.

Laboratory Methods

The moisture content of 25 sites along the tundra transect was determined from soil samples collected at the mid-depth of the maximum 1972 recorded thaw. In accordance with standard practice, the moisture content was obtained by weighing a given sized soil sample before and after drying and expressing the moisture content as a percentage of the dry weight (Buckman and Brady, 1960). Grain size characteristics of samples were determined by using sets of ASTM-approved sieves and hydrometer analysis.

Statistical and Computer Applications

Linear and multiple regression equations were derived using the methods outlined by Snedecor and Cochran (1967) and the Statistical Analysis System (SAS) REGR procedure (Service et al., 1972). Graphs produced by the SAS PLOT procedure were used in the analysis of the data (Service et al., 1972). A Milgo DPS-7 flatbed plotter was used to prepare profiles of the island, polygon, and pond transects.

SEASONAL AND LINEAR VARIATIONS IN THE ACTIVE LAYER

Daily Probes

The rate at which the active layer thawed varied during the summer (Fig. 11). Initially the thickness of the active layer increased rapidly. Reversals occasionally occurred; for example, subzero temperatures during the nights of June 4 to June 6 reduced the thickness of the active layer at station 22N by 3 cm (Fig. 11). However, thaw depths were not affected at stations 2N and 17N because the base of the developing active layer was likely deep enough at these two stations to be below the influence of minor surface temperature changes (Fig. 11).

Diurnal soil temperature fluctuations at station 22N occurred at depths of 20 cm but did not penetrate as deep as 40 cm (Fig. 12). Thus, the rate of flow in the surficial layer, which is subject to diurnal temperatures, may be expected to vary from the thaw rate calculated at depths below the influence of diurnal temperature changes. In the case of station 22N, an apparent change in the rate of thaw occurred when the active layer was between 20 cm and 30 cm thick (Fig. 11). This depth corresponded to the depth of diurnal temperature fluctuations. The thickness of the surficial layer subject to diurnal soil temperature fluctuations will vary according to numerous factors, including vegetation cover, temperature regime, and type and size of sediment. The occurrence of a moderate vegetation cover and an intact organic mat at station 24S combined to act as a good insulator, thereby reducing diurnal soil temperature fluctuations. Readings taken over a 36-hour period in late June showed that, at station 24S, diurnal soil temperature fluctuations did not occur at a depth of 20 cm but did so at depths of 20 cm at the three sparsely vegetated sites (stations 2N, 17N, and 22N) (Fig. 12).

The initial period of rapid thaw was followed by a more gradual thickening of the active layer (Fig. 11). This uniform increase continued until about the last week in July or the first week in August, when the active layer approached its maximum thickness. The rate of thaw for this portion of the season was determined by calculating linear regression equations for stations 2N, 17N, 22N, and 24S for the period June 19 to July 20. The equations, shown in Figure 11, are in the form:

$$Y = a + bX$$

where Y is the predicted depth of thaw
- a is the intercept (i.e., depth of thaw at time zero)
- b is the rate of thaw
- X is the number of days since time zero (i.e., June 19)

The mean daily rate of thaw at station 24S, as expressed in the linear regression equation, was significantly less than at stations 2N, 17N, and 22N. Lower soil

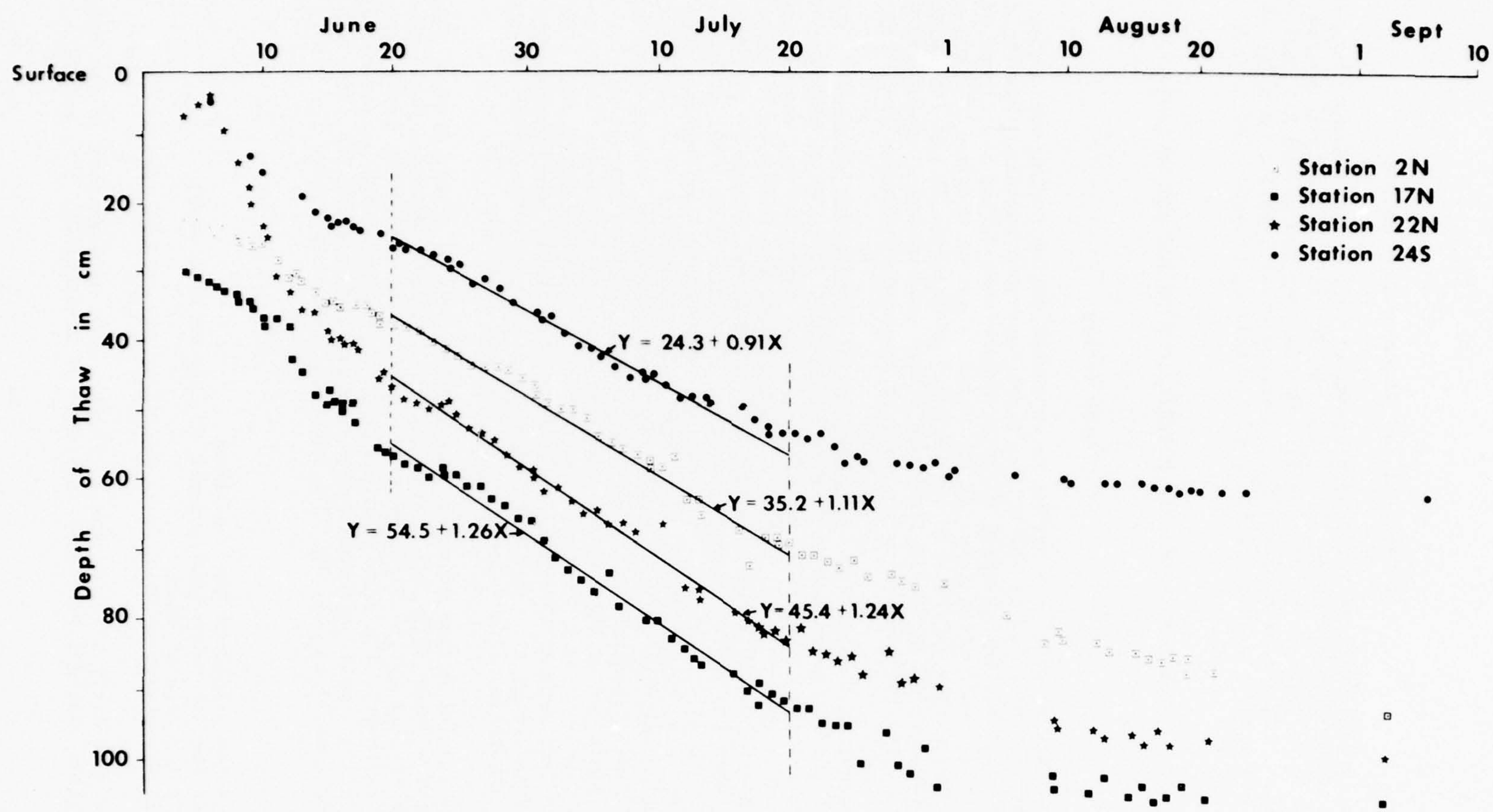


Figure 11. Depth of thaw at stations 2N, 17N, 22N, and 24S, June to September 1972.

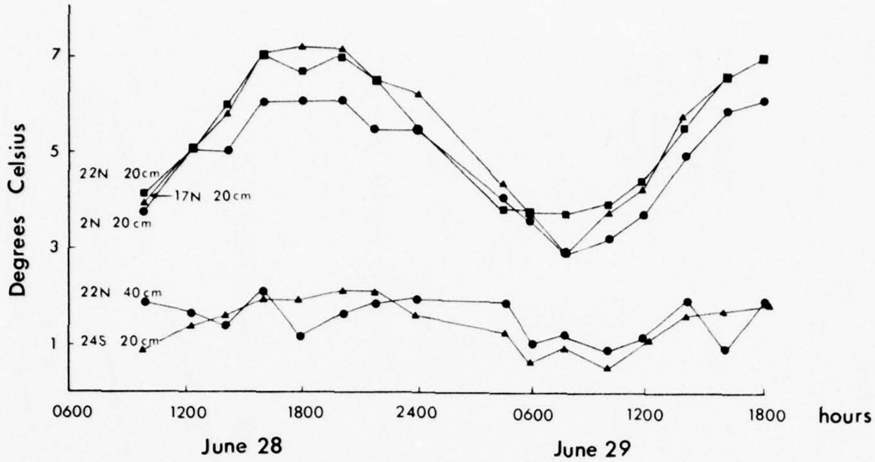


Figure 12. Soil temperatures recorded at station 22N at a depth of 40 cm and at stations 2N, 17N, 22N, and 24S at a depth of 20 cm, June 28-29, 1972.

temperatures at station 24S, as a result of vegetation and organic matter, were largely responsible for the slower thaw rate. Differences in the June 19 depth of thaw occurred at the four stations. As illustrated by the depth of thaw curves for stations 2N and 22N, differences in the June 19 thaw depths were primarily attributable to variations in the rate of the initial thaw (Fig. 11). Variations in the duration of the initial thaw period also may have contributed to differences in thaw depths.

By the second week of August, the rate of thaw had decreased, resulting in a flattening of the depth-of-thaw curves (Fig. 11). This lasted until the start of the freezeback. In the case of station 2N, the active layer continued to deepen, although at a lesser rate; however, at the three other sites the active layer deepened by as little as 4 cm during the entire month of August (Fig. 11).

Although the depth-of-thaw curves are composed of three distinct sections, the shape of the entire curve may nonetheless be described mathematically. Appropriate multiple regression equations were derived for each curve. The resulting coefficients of determination, R^2, which express the proportion of the total variance accounted for by the regression equations, are extremely high; in all cases more than 97 percent of the variance is explained (Table 1). When the regression equations were plotted, they were almost identical to the actual field data; of particular significance is the flattening of the curve once maximum thaw is reached (Fig. 13).

Tundra Transect

Although regression equations could be calculated for depth and rate of thaw at a particular site, there was such a wide variation in thaw depths along the transect that the use of an equation describing the "average" rate of thaw was not practical.

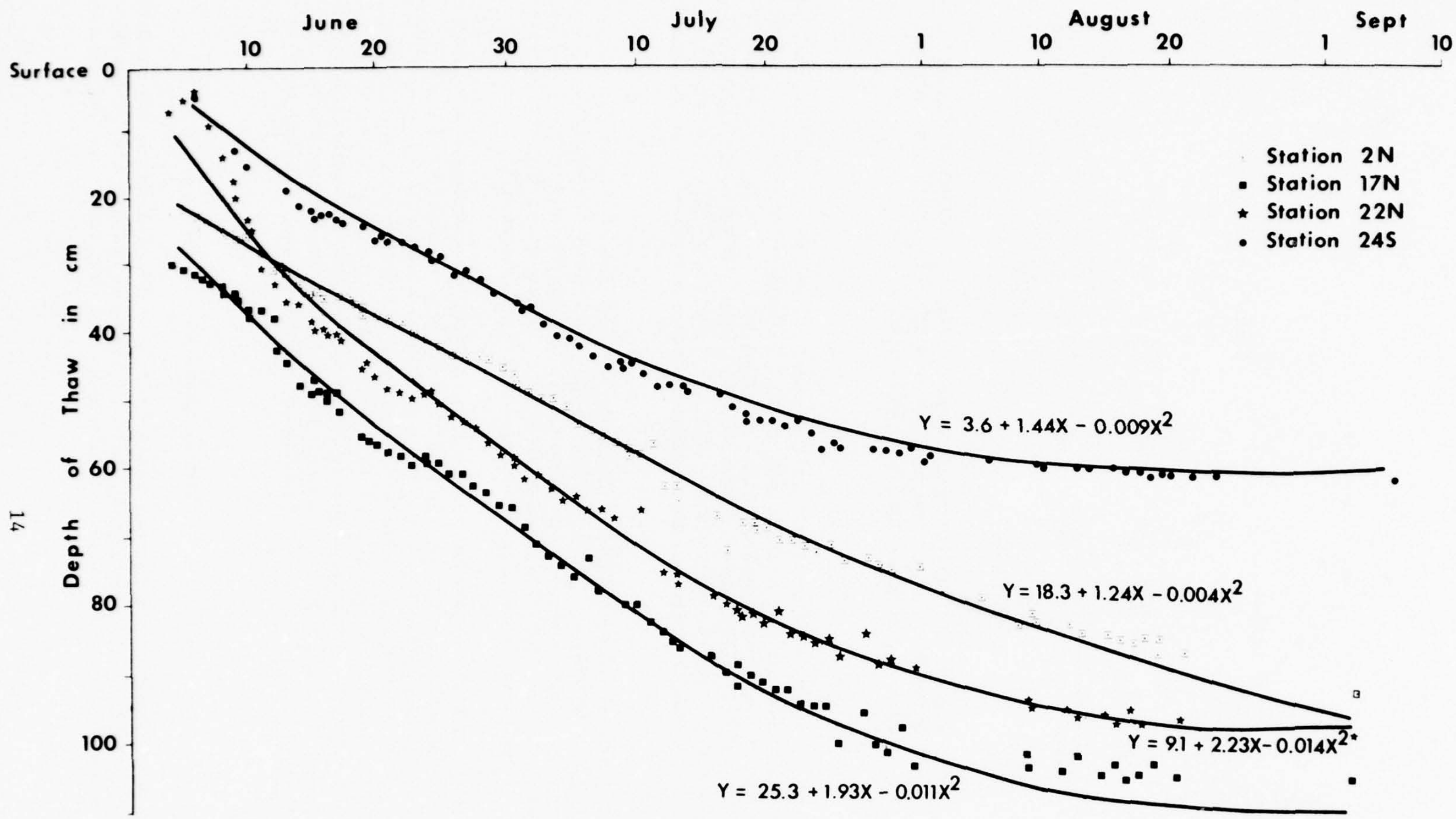


Figure 13. Recorded and predicted depth of thaw at stations 2N, 17N, 22N, and 24S, June to September 1972.

Table 1. Multiple Regression Equations for the Depth of Thaw at Four Stations

Station	Equation	R^2 (%)
2N	$Y = 18.3 + 1.24x - 0.004X^2$	97.9
17N	$Y = 25.3 + 1.93x - 0.011X^2$	98.2
22N	$Y = 9.1 + 2.23x - 0.014X^2$	97.7
24S	$Y = 3.6 + 1.44x - 0.009X^2$	99.1

x and X are the number of days from day 1 (i.e., June 4)

Profiles of the surface configuration and the base of the active layer at various dates along section B were compiled (Fig. 14). Although there was a wide range of thaw depths, the shape of the active-layer profiles, apart from occasional irregularities, resembled the surface configuration. Slightly less relief occurred in the active-layer profiles than on the surface. For example, the maximum surface relief across section B was 87 cm, but the maximum relief within the September 8 thaw profile was 76 cm, 11 cm less than that of the surface. The reduction in relief was primarily the result of a greater thaw beneath topographic highs than occurred beneath surficial depressions and level areas. A computation of the thickness of the active layer every 5 metres along section B shows that, in 70 percent of the cases, a change in surface elevation from the adjacent site resulted in a respective increase or decrease in the depth of thaw. Thus, the shape of the active-layer profiles on Pingok Island generally supports the concept advocated by Brown and Johnson (1965).

The thickness of the active layer was highly variable. The base of the active layer along section B varied from 20 cm to 70 cm below the surface (Fig. 15). If the area were homogeneous, a constant thaw depth would be expected. Abrupt or prominent changes in the shape of the active layer profiles may not produce significant or prominent changes in the thickness of the active layer. For example, near symbol A, Figure 14, the active-layer configuration was very irregular; however, when the thickness of the active layer at the same location was plotted, little change in the depth of thaw was noticed (Fig. 15, symbol A). The result was that the active layer generally conformed to the surface configuration.

Topographic differences along section B of the tundra transect are primarily attributable to permafrost-associated features such as hummocks and polygons. The configuration or shape of the various active-layer profiles under these forms differs greatly.

Hummocks approximately 30 cm in diameter and 10 cm to 20 cm in height occur on Pingok Island. The hummocks are composed primarily of silt- and clay-sized material and are largely devoid of vegetation and contrast to the coarser and more organic soils adjacent to the hummock. Four hummocks occurring along the island transect are identified in Figure 14 by the symbol B. An inversion of the surface configuration develops in the active-layer profiles beneath the hummocks. In two of the four cases indicated, an inversion had developed by the first set of

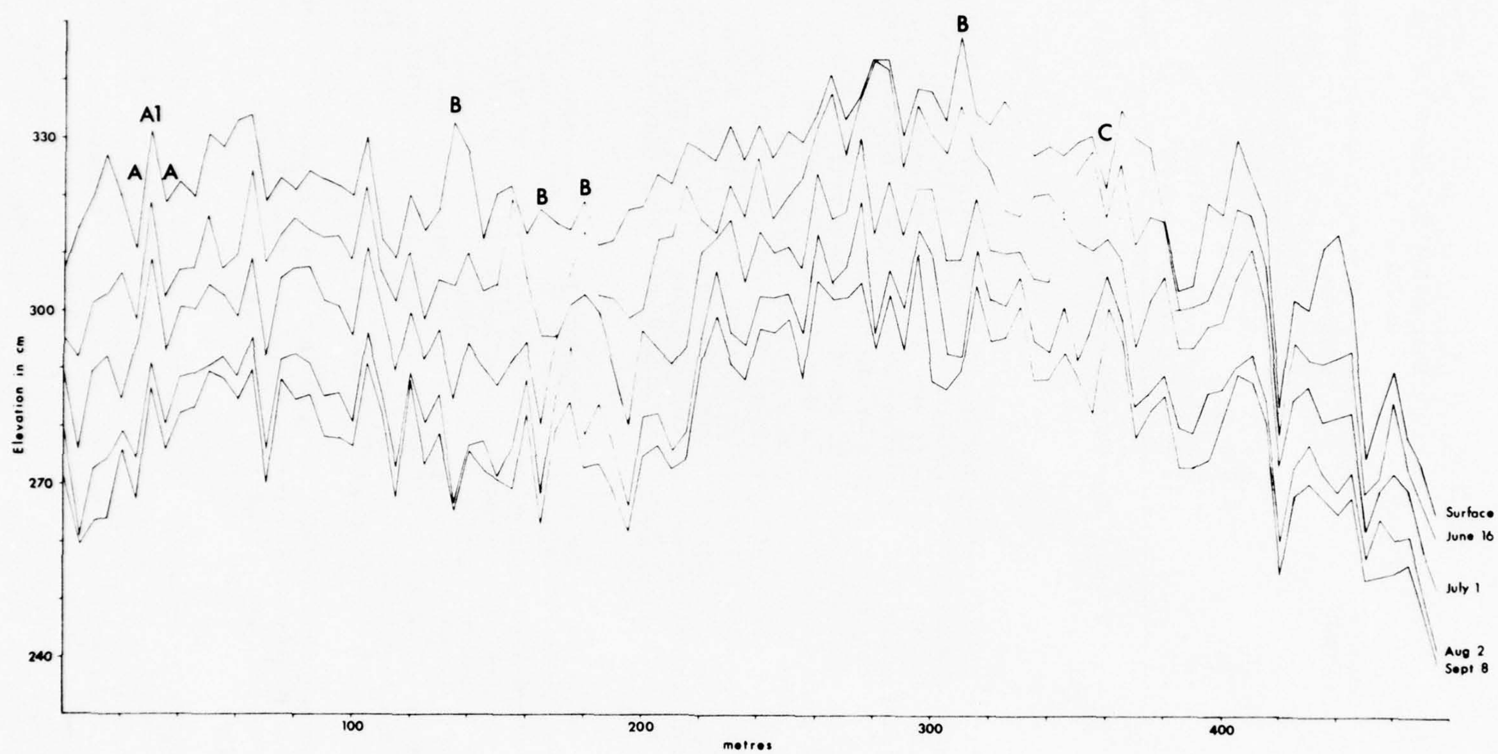


Figure 14. Surface configuration and active layer profiles along section B of the tundra transect.

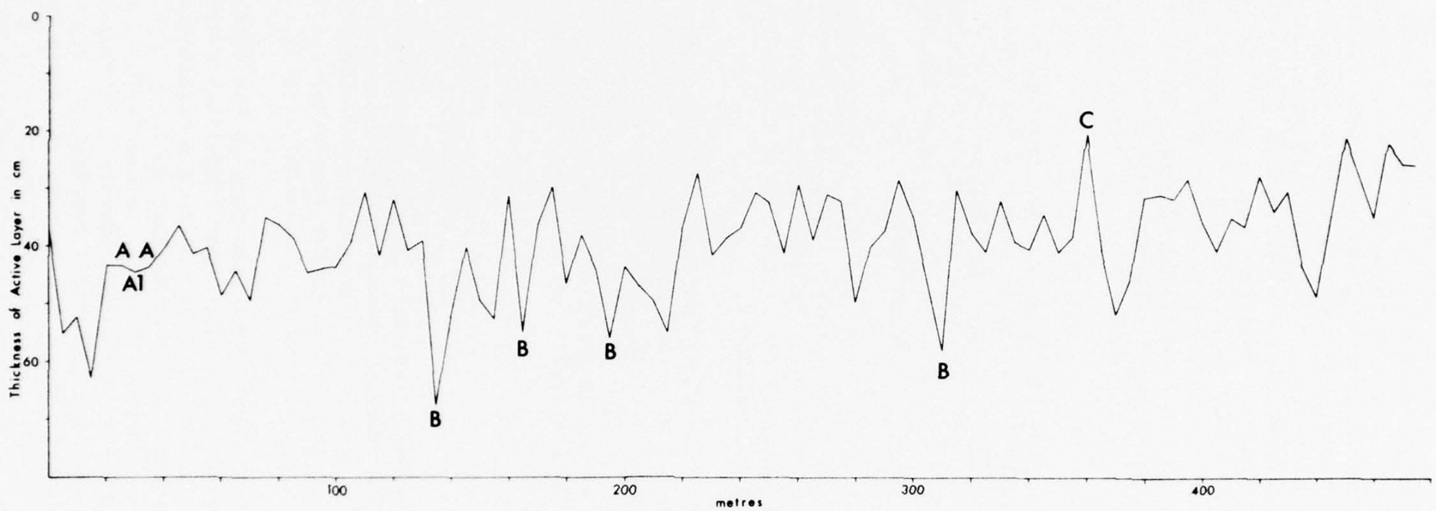


Figure 15. Thickness of the active layer along section B of the tundra transect.

readings on June 16. With each successive profile the inversion was accentuated, so that by mid-July the effect was pronounced. In the other two cases, profiles taken early in the thaw season conformed to the surface topography; however, by the middle of the summer an inversion had developed. Differences in vegetation cover, moisture, or the date of snow melt from the hummock could account for variations in the formation of inverse profiles beneath hummocks. Although the causes of inverse profiles are not clear, Mackay (1958) lists two factors that are partly responsible: (a) greater insulating qualities of the adjacent organic material in comparison with the predominantly mineral soil beneath the hummocks; and (b) evaporation of abundant moisture in the organic material, which maintains low temperatures and a high frost table (Benninghoff, 1952). It is significant that the tops of the hummocks showed little vegetative cover, resulting in higher ground temperatures on top of the hummock than on the adjacent moss- and sedge-covered areas.

Active-layer profiles under polygon troughs and crests generally conformed to the surface configuration (Fig. 14, symbols A and A1), although inverse profiles may develop over ice wedges because the presence of an ice wedge retards the downward movement of the zero-degree isotherm. The thinnest active layer along the island transect occurred in the proximity of an ice wedge where an inverse profile had developed (Figs. 14 and 15, symbol C).

The surface configuration and five depth-of-thaw profiles were also compiled for section A of the tundra transect (Fig. 16). Because the readings were spaced at 1-metre intervals, the plot is more detailed than that presented for section B. Nevertheless, the general remarks concerning the shape of section B profiles are equally applicable to section A.

The greatest thaw along section A of the tundra transect occurred near the start of the transect where the area was only sparsely vegetated. As the percentage of vegetation cover increased, the thickness of the active layer generally decreased. As a result of the combination of a decreased rate of thaw in the polygon troughs (Fig. 16, symbol A) and an increased thaw beneath the crests of polygons (Fig. 16, symbol B), the thaw profiles were a subdued representation of the surface configuration.

Polygon

Polygons are one of the more characteristic features of the Coastal Plain. Although the tundra transect crossed several polygons, the density of measurements was not sufficient to obtain an adequate representation of the shape and thickness of the active layer across a polygon. Accordingly, four transects were established across a typical polygon found on the island (Fig. 17).

The polygon transects exhibited many of the characteristics of the tundra transects. The shape of the September 8 profile, which represented maximum thaw depths, usually conformed with the surface configuration (Figs. 18-21). As noted previously, the active layer was thinner in the polygon trough than at the polygon crests (Figs. 18-21, symbols A and B, respectively). The thickness of the active layer in the vicinity of the polygon crests and troughs was greatly influenced by vegetation, moisture, and geomorphic conditions. Vegetation cover in the troughs was noticeably greater than on the crests, resulting in increased insulation and, hence, a shallower thaw. Because small pools of water are often present in a polygon trough and because soils with high moisture content have a high volumetric heat capacity, they are usually associated with thin active layers. Geomorphic

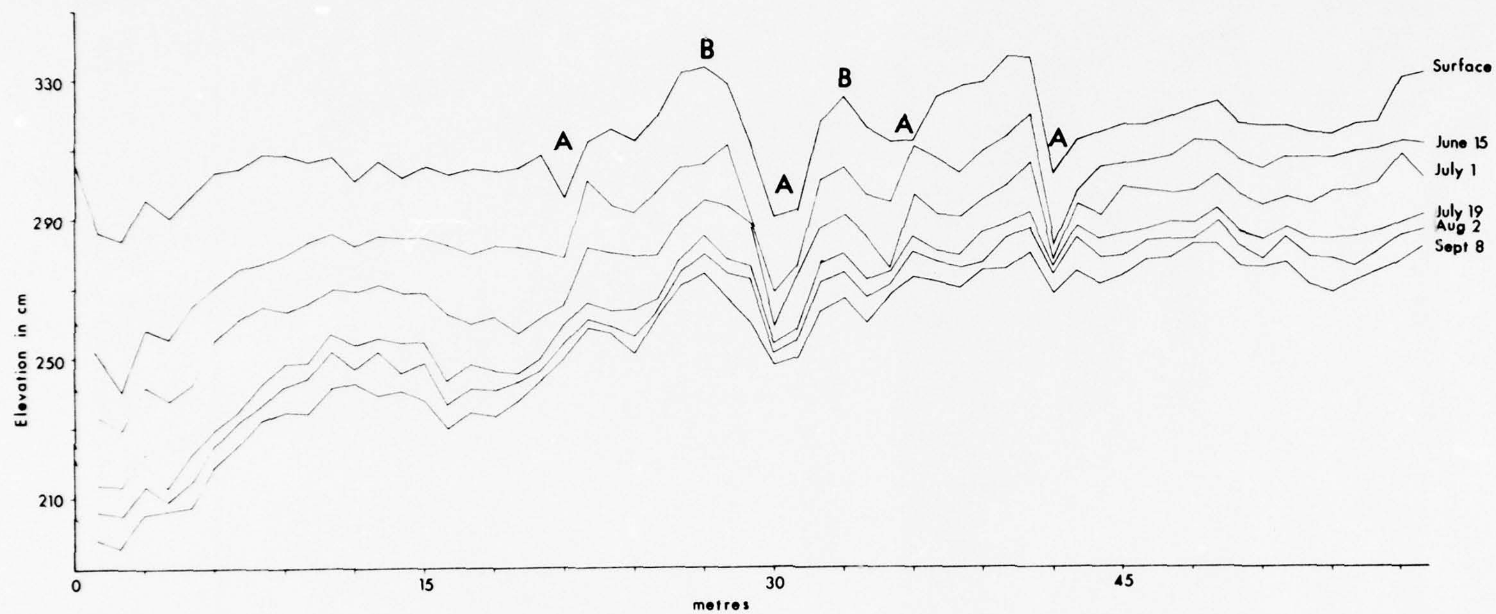


Figure 16. Surface configuration and active layer profiles along section A of the tundra transect.

Figure 17. View of polygon (view to the east). Sticks indicate location of transects across the polygon.

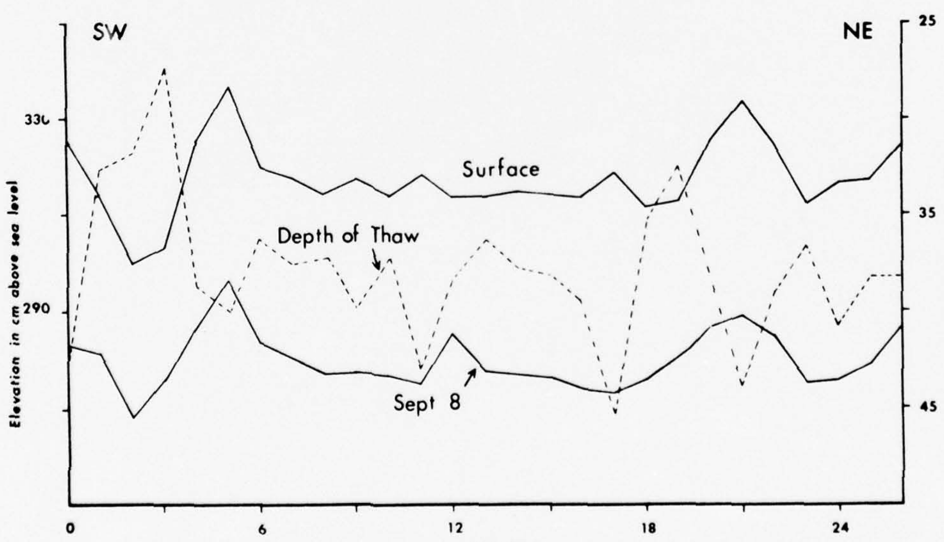


Figure 18. Elevation, shape, and depth of thaw across a polygon, southwest to northeast profile.

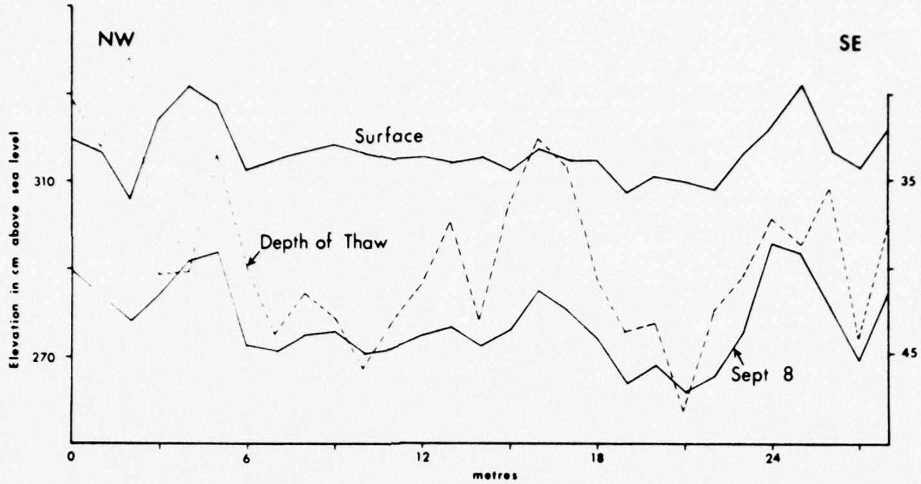


Figure 19. Elevation, shape, and depth of thaw across a polygon, northwest to southeast profile.

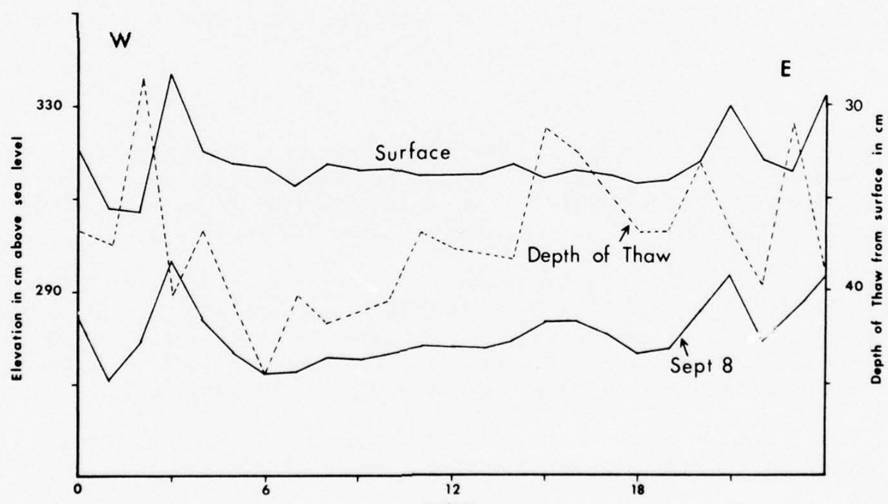


Figure 20. Elevation, shape, and depth of thaw across a polygon, west to east profile.

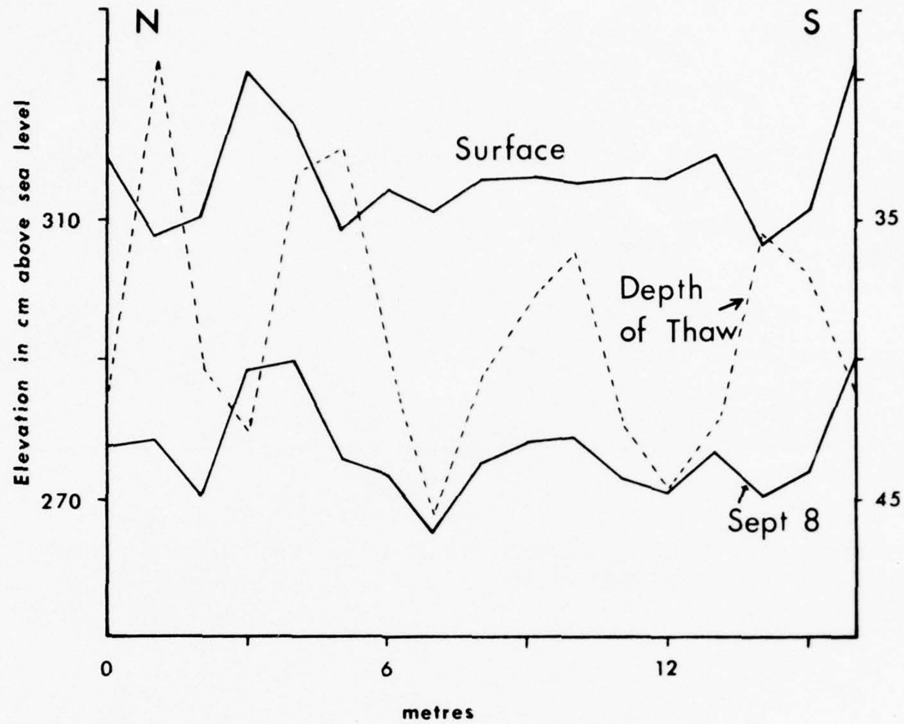


Figure 21. Elevation, shape, and depth of thaw across a polygon, north to south profile.

conditions may also be important in some circumstances. For example, the presence of an ice wedge near the surface will result in an abnormally thin active layer. Involutions formed by cryogenic processes and changes in lithology are also causes of variations in the thickness of the active layer (Tumel, 1973).

The central area of the polygon was flat, apart from occasional frost mounds (Fig. 18, symbol C). Because the frost mounds within the polygon were not as large as the hummocks discussed previously, the increase in thaw depths beneath the mound was not sufficient to produce an inverse profile; therefore, the resulting profile remained as a subdued representation of the surface configuration.

FACTORS AFFECTING ACTIVE LAYER DEVELOPMENT

Exposure

Although slope exposure has been recognized as an important influence on microclimate and vegetation, few studies are available that assess the importance of solar radiation to the thickness of the active layer.

In the present study snow-drift accumulations on both north- and south-facing slopes delayed the start of thaw on those slopes (Fig. 22). However, the prevailing

Figure 22. Sand dune complex where slope exposure readings were taken (view to northeast). (Note snow patches on lee side of dunes, far right.)

wind kept the southwest slope relatively snow free, and, as a result, the deepest thaw during June was on the southwestern exposure. By August the thickest active layer had occurred on the south-steep slope, and similar depths of thaw were recorded on the southwest and south-gentle slopes (Table 2). The maximum thaw recorded for each slope occurred at or near the crest of the slope. In this region, heat was conducted downward from the crest and also horizontally from the slope. Thus, heat was being added to the soil from two directions, thereby accounting for the greater depth of thaw.

Probe measurements indicated that southwest slopes had thicker active layers than southeast slopes. This finding agrees with those of Price (1971) but contrasts with those of French (1970), who noted that at his study area southeast slopes had significantly deeper active layers than southwest slopes. Probes indicated that the northwest aspect generally had a greater thaw than the northeast exposure, although on the lower portion of the slope the thaw depths were similar.

Theoretically, the thinnest active layer should occur on the north slope; however, probe measurements indicated that the active layer was thinner on northwest and northeast slopes (Table 2). As the northwest and northeast slopes were located about 0.5 km west of the other slope exposures, environmental factors may have modified their depth of thaw.

South-facing slopes may be expected to have a greater thaw than north slopes; however, microenvironmental conditions may substantially alter the rate and depth of thaw. For example, Price's (1971) study in alpine tundra indicated that the

Table 2. Angle of Slope and Thaw Depths on Various Exposures

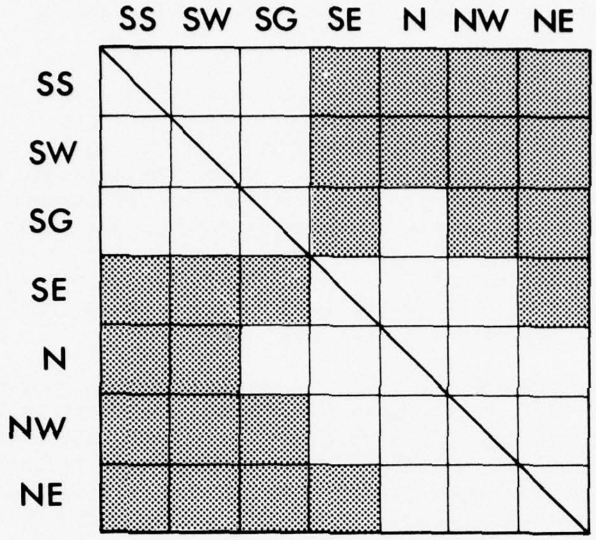
Exposure	Degree	Depth of Thaw	
		Maximum	Mean
South-steep	22	167	138
Southwest	13	142	128
South-gentle	10	136	122
Southeast	11	135	109
North	21	138	106
Northwest	22	129	100
Northeast	16	103	92

See Appendix B for profiles of the slopes and active layer topography.

effect of exposure may be of less importance than vegetational changes. Microclimatic conditions, especially the duration and speed of the prevailing wind, can have more influence on the depth of thaw than the aspect of the site may have (French, 1970). Therefore, predictions of the rate and depth of thaw on various exposures based solely on the aspect of the site, without regard to vegetational, microclimatic, or other environmental factors, must be tentative and subject to revision.

The slope exposure data were subjected to statistical tests to determine the importance of insolation to the depth of thaw. Differences between mean depths of thaw recorded on August 19 were examined by Student's t-test at the 0.05 level of significance. Statistically, the south-steep and southwest slopes had a significantly greater thaw than the three northerly exposures (Fig. 23). The southeast slope, because it received direct solar radiation only during the morning, before air temperatures had reached their diurnal maximum, had a relatively thin active layer. As a result, thaw depths on the southeast exposure were not significantly different from those on the north and northwest slopes (Fig. 23). Radiation differences would theoretically cause a significant difference between thaw depths on the diametrically opposed north and south-gentle slopes. However, a wide range of thaw depth was recorded on the north slope, which resulted in a high coefficient of variation, and thus no significant difference ($p = 0.05$) was found between the thickness of the active layer on the north and south-gentle exposures (Fig. 23).

Radiation differences also led to variations in the thickness of the active layer among the four southerly exposures. The southwest slope, in contrast to the southeast slope, received most of its direct solar radiation during the mid-afternoon at a time when air temperatures were usually near their diurnal maximum. As a result, the southwest exposure showed significantly greater thaw than the southeast slope. Similarly, radiation differences caused thaw depths on the south-steep and south-gentle slopes to be significantly greater ($p = 0.05$) than those on the southeast exposure. However, the comparative warmth of the southwest exposure resulted in no significant difference between it and either the south-steep or the south-gentle slopes (Fig. 23).



Legend

Solid blocks indicate a significant difference at the 0.05 level

Blank blocks indicate no significant difference at the 0.05 level

SS = south-steep exposure
SW = southwest exposure
SG = south-gentle exposure
SE = southeast exposure
N = north exposure
NW = northwest exposure
NE = northeast exposure

Figure 23. Significance of mean thaw depths on various exposures.

In contrast to the southerly exposures, the three northerly slopes, which received little direct solar radiation, had statistically similar mean thaw depths.

In summary, the statistical tests indicated that thaw depths on the south-steep, south-gentle, and southwest exposures were generally significantly different from the three northerly exposures and the southeast slope. Thus, slope orientation is confirmed as a factor in influencing the thickness of the active layer.

Pond

Data collected by Lewellen (1972) indicate that the depth of thaw beneath shallow flowing streams in the Barrow area may be three times the thickness of the active layer at sites adjacent to the stream. However, Dingman (1973) did not find

any appreciable difference between the thickness of the active layer under a small stream and at adjacent sites.

In the present study, depth-of-thaw readings taken across a small pond on Pingok Island (Fig. 24) showed that, although the pond surface remained frozen longer than the surrounding tundra, thaw progressed so rapidly that by July 8 the depth of thaw was greater beneath the pond than on the adjacent tundra. The second set of readings, in addition to confirming the presence of a thicker active layer beneath the pond than on the surrounding tundra, indicated that from July 8 to August 7 the thickness of the active layer beneath the pond and at adjacent sites increased by approximately 1.5 times. Thus, although there was a greater thaw beneath the pond than at adjacent tundra sites, the proportional increase in the depth of thaw was approximately the same (Fig. 25).

Danks (1971) reported that water temperatures in shallow ponds are very similar to nearby ground surface temperatures. In addition, the upper 1 cm to 20 cm of mud on the bottom of a pond is almost as warm as the bottom water (Danks, 1971). On the adjacent tundra, the vegetation cover reduces absorption and an aerated organic mat acts as a good insulator by reducing the amount of heat conducted down into the soil. The result is less thaw beneath tundra surfaces than beneath shallow ponds.

Vegetation

As the relationship between vegetation and depth of thaw is often readily noticeable in the field, numerous observations relating vegetation to permafrost conditions are found in the literature. It is well documented that the removal of vegetation from a site increases the depth of thaw (Brown, 1965; Bliss and Wein, 1972). The data collected on Pingok Island substantiated many of the published findings of others. For example, nonvegetated sites (those with less than 5 percent vegetation cover) had thick active layers. Brown (1965, 1966) showed that the depth of thaw is greatly influenced by the thickness of moss and peat, whereas the influence of other vegetation is believed to be minor. Thus, if a site has a low vegetation cover but a substantial surficial peat layer, a shallow depth of thaw

Figure 24. Small pond on Pingok Island, looking northwest. (Sticks indicate location of transect across the pond.)

will occur. This occurred at several sites on Pingok (Fig. 26, Symbols A, B, C). In other instances, however, a low vegetation cover associated with poorly drained areas will also result in a thin active layer (Fig. 26, Symbols D, E).

Vegetated areas on Pingok Island are usually associated with active layers 30 cm to 60 cm in maximum thickness. Variations in depth-of-thaw readings are often attributable to other factors such as terrain conditions, although Brown (1966) has suggested that minute but possibly significant variations within a particular type of vegetation may be associated with changes in the depth of thaw.

Moisture Content

As ice-rich soils have a higher volumetric heat capacity than dry soils, they require more energy to thaw to similar depths. Brown (1969) found a highly significant negative correlation between the total moisture content of thawed soil and depth of thaw penetration. However, the samples collected on Pingok Island revealed that sites with high moisture contents usually have thin active layers, whereas sites with low moisture contents have variable active layers (Fig. 27).

Sediment Size

Changes in the thickness of the active layer are frequently associated with corresponding changes in sediment size (Mackay, 1970). Although samples collected on Pingok Island showed a general trend for coarser sediments to have thicker active layers than fine-grained sediments, the correlation was not strong (Fig. 28). Part of the scatter of points was attributable to factors other than grain size. For example, the difference in thaw depths between sites A and B, which showed similar graphic means, was partially attributable to vegetation cover. Vegetation cover at site A was estimated at 10%, whereas at site B vegetation covered 100% of the site and significantly lower soil temperatures and a thinner active layer resulted.

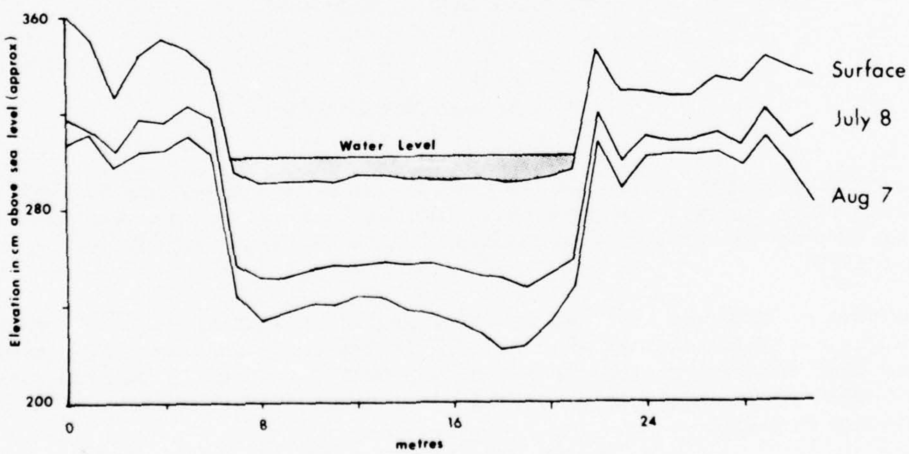


Figure 25. Elevation and shape of the active layer across a pond.

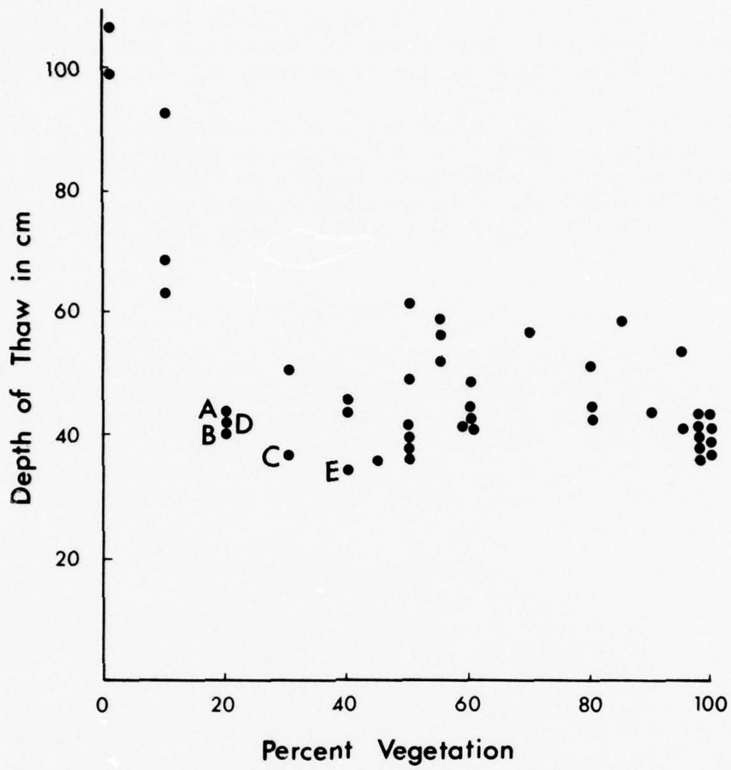


Figure 26. Depth of thaw and percentage of vegetation cover for selected sites on Pingok Island.

SUMMARY AND CONCLUSIONS

The rate and depth of the annual thaw of the active layer are controlled by several climatic, biotic, and geomorphic factors. These factors were examined by a number of systematic surveys of the depth of thaw on Pingok Island during the summer of 1972.

The rate of thaw was recorded by daily probes at four sites and by weekly probes along a transect across the island. It was found that initial thaw was rapid and that the rate of thaw decreased exponentially until a maximum depth was reached. This relationship held for all sites examined, regardless of the maximum depth of thaw attained.

Local variations affected the exponential rate of thaw and the shape and thickness of the active layer. These environmental factors may be summarized as follows:

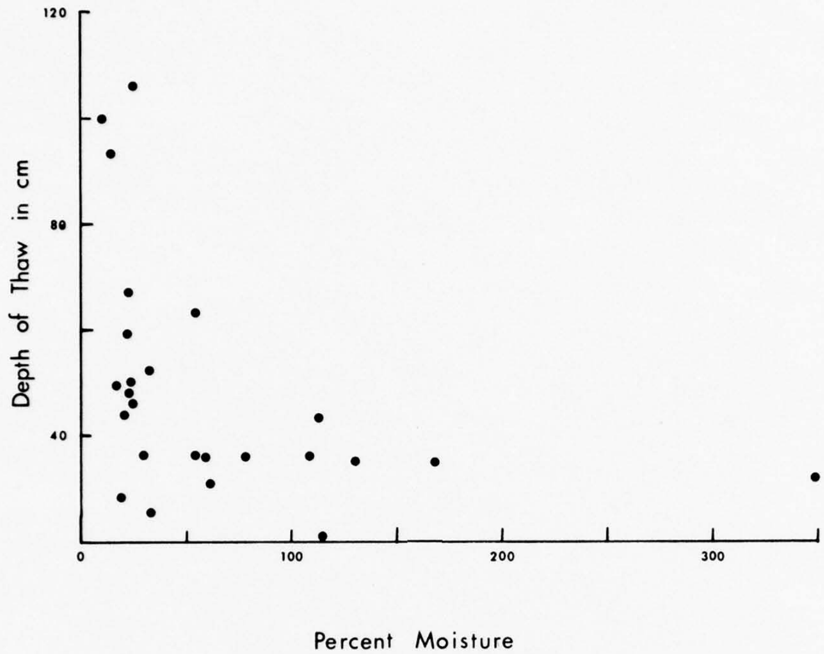


Figure 27. Depth of thaw and percentage of moisture content for selected sites on Pingok Island.

1. Climate, as evidenced by the trend to thinner active layers with increasing latitude, governs the maximum depth of thaw; however, local climatic variations result in a large diversity of depth-of-thaw readings. Two examples of climatic conditions that lead to a reduction in the thickness of the active layer are (1) prevailing winds off an ice pack resulting in lower summer temperatures and (2) reduction in the amount of solar radiation received because of frequent fogs.

2. The active layer generally conforms to the surface configuration. However, as the active layer thickens, there is a tendency for the profiles to become subdued. Large variations in the shape and thickness of the active layer are usually related to surface relief changes, such as polygons and hummocks.

The angle of slope affects the amount of solar radiation received, and hence the depth of thaw. On Pingok, the south-steep slope formed a greater effective angle of incidence with solar radiation than the south-gentle slope and therefore had a thicker active layer.

3. Exposure was shown to be a significant factor in affecting thaw depths. Statistical tests indicated that most southerly aspects have a significantly greater thaw than northerly exposures. Insignificant differences exist between thaw depths on slopes with southeastern, northern, and northwestern exposures.

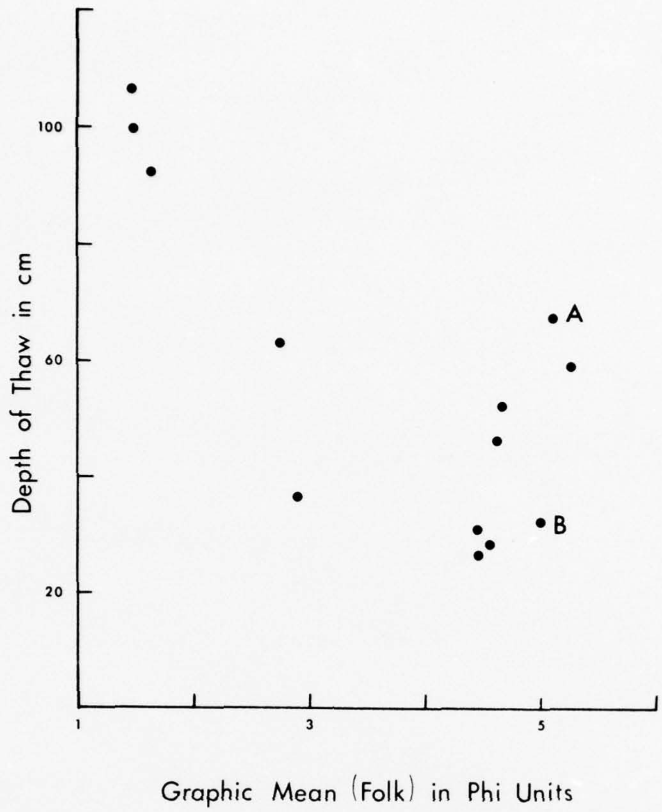


Figure 28. Depth of thaw and graphic mean (Folk) for selected sites on Pingok Island.

4. Observations across a shallow pond indicated that the thaw table resembles the surface configuration. Although the depth of thaw is greater beneath the pond than at adjacent tundra sites, the proportional increase in the depth of thaw during July is approximately the same at both localities. In northern Alaska, most lakes and rivers deeper than about 2 metres are not underlain by permafrost. Because a vastly different thermal regime results, it is important to distinguish between water bodies underlain and those not underlain by permafrost.

5. Vegetation cover, particularly the presence of moss or peat, greatly reduces the depth of thaw at a site. Unvegetated sites on Pingok Island may have thaw depths in excess of 100 cm, whereas in vegetated areas maximum thaw depths are usually 30 cm to 60 cm.

6. Soils with a high moisture content are associated with thin active layers, whereas low moisture contents occur in soils of variable active layer thickness.

7. Sediment size appears to have some effect on the depth of thaw inasmuch as there is a general trend for coarser sediments to have thicker active layers than finer sediments.

The relative importance of the above environmental conditions may vary both temporally and spatially. Temporally, the rate of thaw and the shape of the active layer may be influenced by variations in the above seven conditions. The importance of each condition may also vary spatially. The effects of vegetation, for example, are reported to be greater in the taiga than in the tundra (Brown, 1966), and in some coastal areas the effects of exposure may be of prime importance (French, 1970).

The most important factor affecting the depth of thaw is climate; however, within one climatic region other environmental conditions become prominent. As the presence or absence of vegetation on Pingok Island markedly influenced thaw depths, vegetation must be considered the dominant environmental factor affecting thaw depths on the island. However, the actual shape of the active layer, as shown throughout this study, is dependent on the surface morphology.

Inter-relationships exist among some of the factors that influence the depth of thaw. For example, on sand dunes, low vegetation cover, comparatively coarse sediment, and low moisture contents all contribute to a thick active layer.

The results presented in this study differ somewhat from those presented in the literature for other coastal areas (e.g., Brown, 1969; French, 1970). However, the location of Pingok Island, roughly halfway between Barrow and the Alaska-Yukon border, makes it the ideal representative of the northeastern Alaskan coast.

Because most research on the shape and thickness of the active layer has been concentrated during the thaw season, few studies are available on the freezeback. Future studies on the active layer should, in part, be concerned with freezeback because the evidence at present shows that the form and rate of freezeback are greatly different from those of thaw.

Although there is little published field data, and discrepancies exist concerning the behavior of the active layer, theoretical studies on the shape and thickness of the active layer, especially with respect to pipelines, have been produced. The result is a disconcerting lack of basic information on the development of the active layer at a time of increasing economic activity in permafrost areas.

APPENDIX A

List of Plants Collected on Pingok Island

Alopecurus alpinus

Arctagrostis latifolia

Arnica sp.

Cardamine digitata

Carex aquatilis

Cochlearia officinalis

Dryas intergrifolia

Elymus arenarius ssp. mollis

Eriophorum angustifolium

Melandrium apetalum

Papaver radicatum

Pedicularis lanata

Petasites frigidus

Poa sp.

Poa alpigena

Polygonum viviparum

Rumex arcticus

Salix arctica

Salix pulchra

Salix phlebophylla

Salix ovalifolia

Saxifraga cernua

Saxifraga foliolosa

Saxifraga hieracifolia

Saxifraga hirculus

Saxifraga oppositifolia

Stellaria longipes

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APPENDIX B

Elevation and Shape of the Active Layer on Seven Exposures

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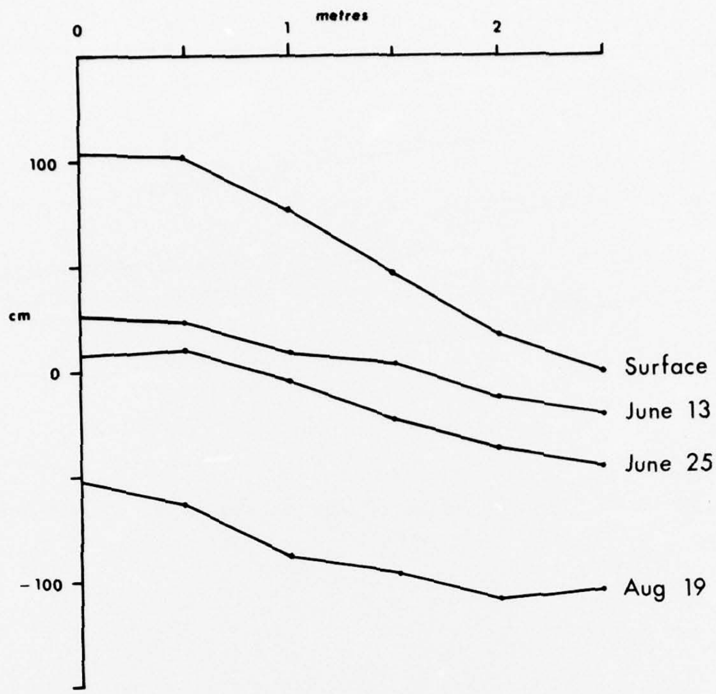

Figure B-1. Elevation and shape of the active layer on the south-steep exposure.

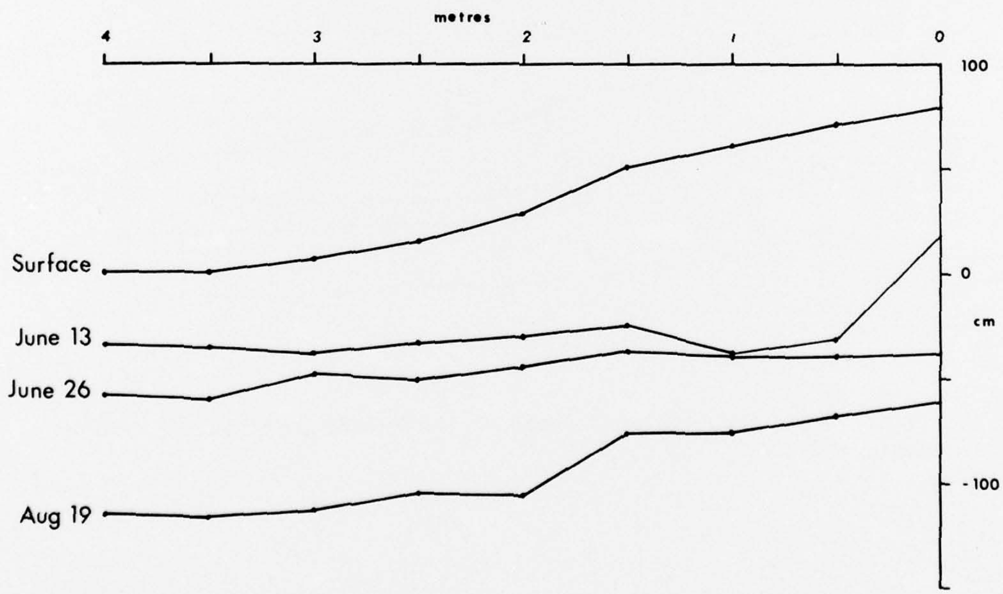

Figure B-2. Elevation and shape of the active layer on the southwest exposure.

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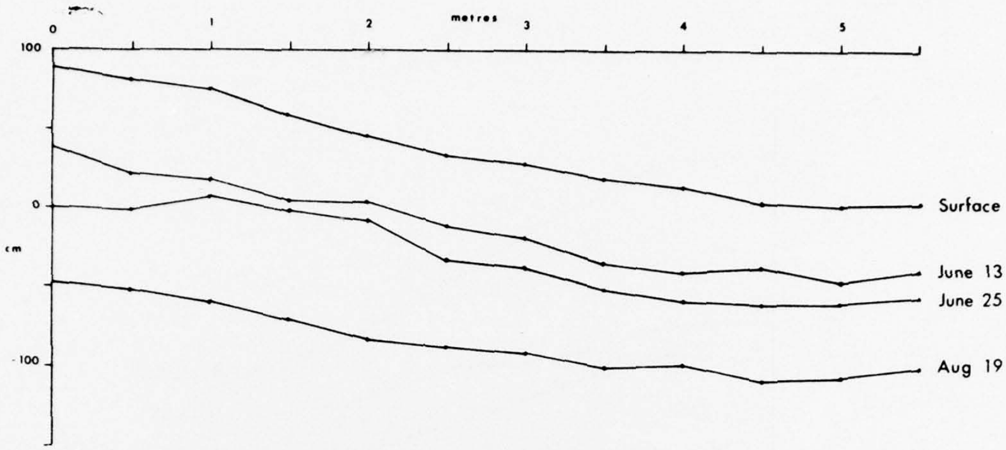

Figure B-3. Elevation and shape of the active layer on the south-gentle exposure.

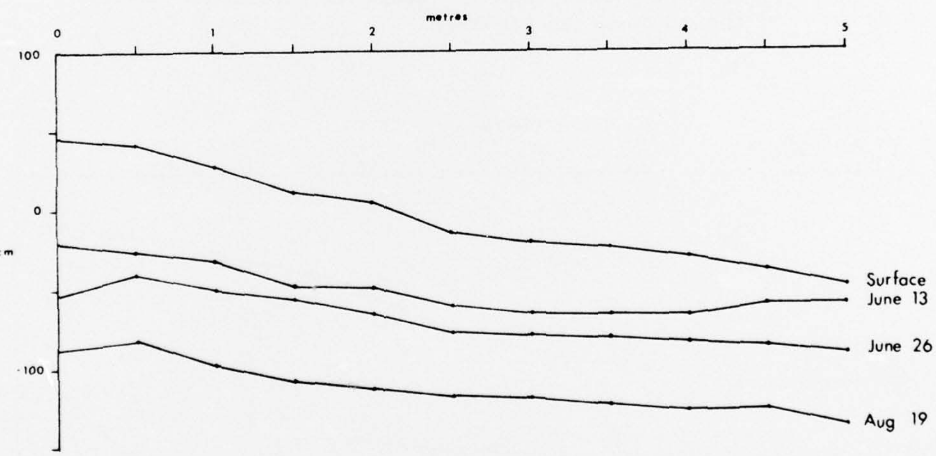

Figure B-4. Elevation and shape of the active layer on the south-east exposure.

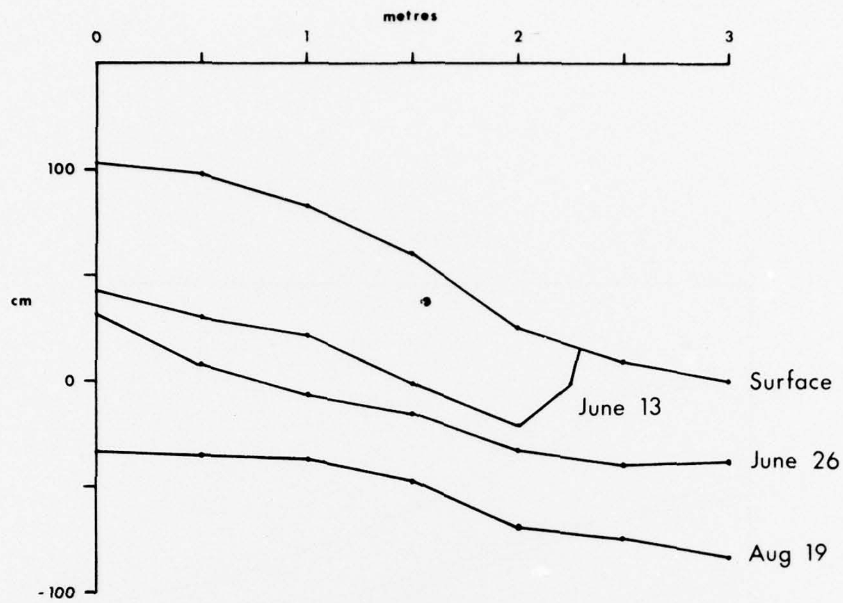

Figure B-5. Elevation and shape of the active layer on the north exposure.

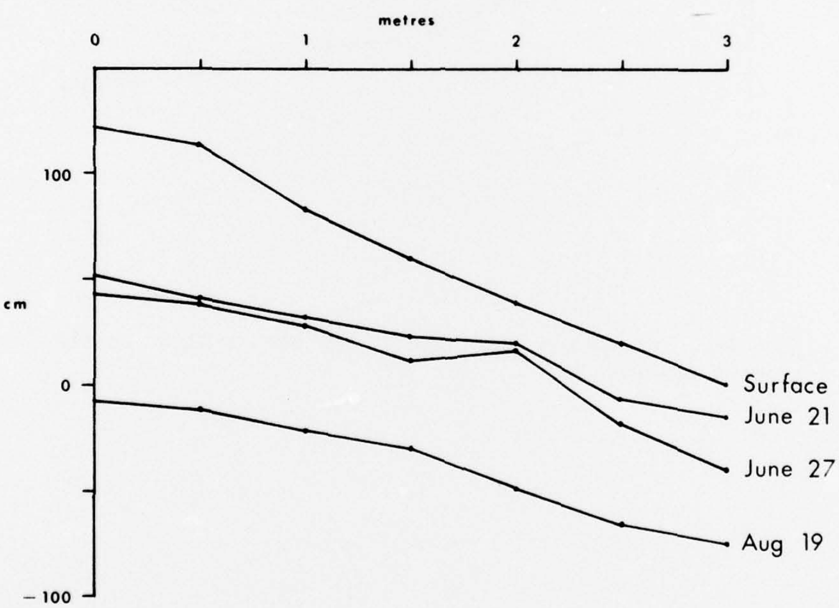

Figure B-6. Elevation and shape of the active layer on the northwest exposure.

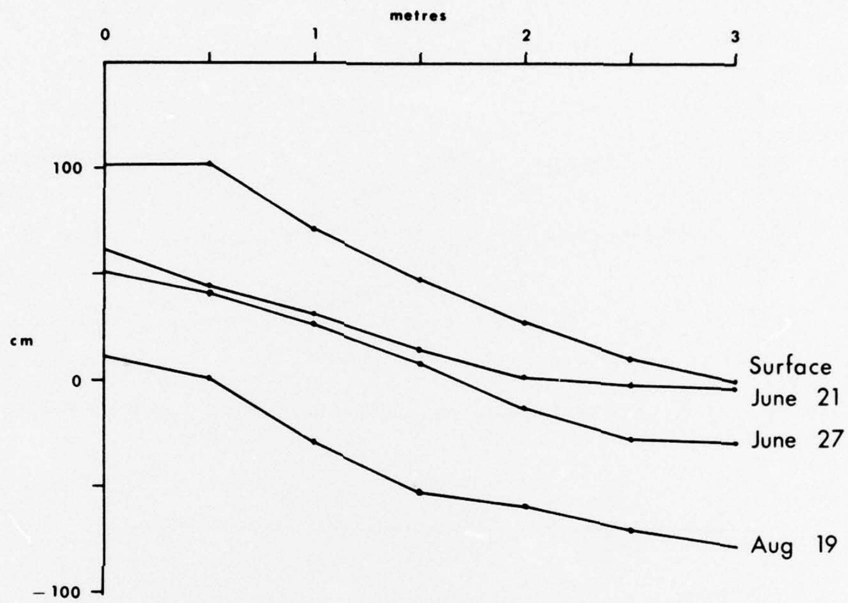

Figure B-7. Elevation and shape of the active layer on the northeast exposure.

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13. ABSTRACT

Depth-of-thaw measurements were made on Pingok Island, Alaska, throughout the 1972 thaw season. The research revealed that initial thaw is rapid and the rate decreases exponentially until a maximum depth is reached. Generally, the base of the active layer conforms to the surface configuration; however, local variations in the rate of thaw affect the shape and thickness of the active layer. An inversion of the surface topography often develops beneath hummocks that have a low vegetation cover and over ice wedges that are close to the surface. Slope exposure was found to be significant in affecting the thickness of the active layer, whereas moisture content and sediment size of the range discovered on Pingok Island have only minor effects on the depth of thaw. Thaw depths beneath a shallow pond were found to be greater than on the surrounding tundra. The dominant factor in influencing the thickness of the active layer in the study area is considered to be the presence of a vegetation cover.

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